TUTORIAL 12

1 Homework 9

Show that for any $\rho \in \mathbb{C}^{d\times d}$, there exists quantum channels $C : \mathbb{C}^{d\times d} \to \mathbb{C}$ and $D : \mathbb{C} \to \mathbb{C}^{d\times d}$ such that:

$$\Delta(D(C(\rho)), \rho) = 0 \; .$$

2 Shannon Channel Coding Theorem

The goal of this tutorial is to prove Shannon channel coding theorem. First, recall the definition of a code and the capacity of a channel:

Definition 2.1. *A (n, R, δ) code for the channel $W = \{W(y|x)\}_{x\in\mathcal{X},y\in\mathcal{Y}}$ is a pair E, D such that:*

1. *$E : \{0, 1\}^{Rn} \to \mathcal{X}^n$,*
2. *$D : \mathcal{Y}^n \to \{0, 1\}^{Rn}$,*
3. *With $x^n = x_1 \dots x_n$, $y^n = y_1 \dots y_n$ and $W^n(y^n|x^n) := W(y_1|x_1)W(y_2|x_2)\dots W(y_n|x_n)$:*

$$\frac{1}{2^{Rn}} \sum_{s\in\{0,1\}^{Rn}} \sum_{y^n\in\mathcal{Y}^n : D(y^n)=s} W^n(y^n|E(s)) \geq 1 - \delta \; .$$

It describes the average over all messages s of the probability of successfully decoding s, using n independent copies of the channel W.

Definition 2.2. *For a given channel $W = \{W(y|x)\}_{x\in\mathcal{X},y\in\mathcal{Y}}$, define the capacity of W by:*

$$C(W) = \max_{P_X} I(X : Y) \; ,$$

where the joint distribution over X, Y is defined by $P_{XY}(x, y) = P_X(x)W(y|x)$.

Theorem 2.3 (Shannon Channel Coding Theorem)**.** *For $R < C(W)$, there exists a sequence of (n, R, δ_n) codes for W with $\delta_n \underset{n\to+\infty}{\to} 0$.*

2.1 The decoder

We will assume that $R < C(W)$ is fixed. Let P_X achieving the maximum in the definition of $C(W)$, and define $P_{XY}(x, y) = P_X(x)W(y|x)$. We will first assume that the encoder E is given:

1. What is the best choice for D?

   However, this expression is hard to analyse. We will rather use the following decoder:

$$D(y^n) = \begin{cases} s & \text{if there is a unique } s \text{ such that } W^n(y^n|E(s)) \geq \alpha(n, y^n) \; , \\ s_0 & \text{otherwise.} \end{cases}$$

   where $\alpha(n, y^n)$ will be defined later.

2. Give an expression for $P_{\text{err},s}$, the probability of error for message s.

3. Prove that $P_{\text{err},s} \leq P^1_{\text{err},s} + P^2_{\text{err},s}$, with:

$$P^1_{\text{err},s} := \sum_{y^n \in \mathcal{Y}^n} W^n(y^n|E(s)) \mathbf{1}_{W^n(y^n|E(s)) < \alpha(n,y^n)}$$
$$P^2_{\text{err},s} := \sum_{y^n \in \mathcal{Y}^n} W^n(y^n|E(s)) \sum_{s' \neq s} \mathbf{1}_{W^n(y^n|E(s')) \geq \alpha(n,y^n)}$$

2.2 The encoder

We will use the *probabilistic method* to choose the encoder. For any message s, we will take $E(s) = x_1 x_2 \dots x_n$, where all x_i are chosen independently following the law P_X. The global encoding scheme is E where all $E(s)$ are chosen independently following the previous distribution.

Our objective is to show that $\mathbb{E}_E[P_{\text{err}}] \underset{n \to +\infty}{\rightarrow} 0$, where $P_{\text{err}} = \frac{1}{2^{Rn}} \sum_{s \in \{0,1\}^{Rn}} P_{\text{err},s}$.

1. How can you prove Theorem 2.3 if you have $\mathbb{E}_E[P_{\text{err}}] \underset{n \to +\infty}{\rightarrow} 0$?

2. Let us take now $\alpha(n, y^n) = K(n, \varepsilon) P_{Y^n}(y^n)$, where $K(n, \varepsilon)$ will be defined later, with:

$$P_{Y^n}(y^n) = \sum_{x^n \in \mathcal{X}^n} P_{X^n Y^n}(x^n, y^n) = \sum_{x^n \in \mathcal{X}^n} P_{X^n}(x^n) W^n(y^n|x^n) \ .$$

   (a) With iid. variables $X_i Y_i$ following distribution P_{XY}, show that:

$$\mathbb{E}_E[P^1_{\text{err},s}] = \mathbb{P}\left(\prod_{i=1}^n W(Y_i|X_i) < K(n,\varepsilon) \prod_{i=1}^n P_Y(Y_i) \right) \ .$$

   (b) Define $i_{XY}(x,y) := \log\left(\frac{P_{XY}(x,y)}{P_X(x) P_Y(y)}\right)$. What is the value of $\mathbb{E}[i_{XY}(X_i, Y_i)]$?

   (c) Show that:

$$\mathbb{E}_E[P^1_{\text{err},s}] = \mathbb{P}\left(\sum_{i=1}^n i_{XY}(X_i, Y_i) < \log(K(n,\varepsilon)) \right) \ .$$

   (d) Using the weak law of large numbers[1], give some sufficient conditions on $K(n, \varepsilon)$ to have $\mathbb{E}_E[P^1_{\text{err},s}] \underset{n \to +\infty}{\rightarrow} 0$.

3. Give an upper bound on $\mathbb{E}_E[P^2_{\text{err},s}]$ depending on $K(n, \varepsilon)$, and give some sufficient conditions on $K(n, \varepsilon)$ to have $\mathbb{E}_E[P^2_{\text{err},s}] \underset{n \to +\infty}{\rightarrow} 0$.

4. Conclude.

2.3 An application

1. Compute $C(W)$ for the bit flip channel W, ie. $W(b|b) = 1 - f, W(\bar{b}|b) = f$ for $b \in \{0,1\}$ and $f \in [0,1]$.

[1] If X_i are iid., then $\mathbb{P}\left(\left|\frac{1}{n}\sum_{i=1}^n X_i - \mathbb{E}[X_1]\right| < \varepsilon\right) \underset{n \to +\infty}{\rightarrow} 1$